

Building Rugged Equipment for Use in Caves

In another of our 'Fundamentals' series, **David Gibson** describes the problems of building equipment for use in caves. Waterproofing is a big issue, but he also considers the choice of battery and some problems associated with switches and connectors. These notes are aimed at student electronic engineers who might be building equipment for use in caves as a practical element of their degree course.



These notes are aimed at electronic engineering students who are building equipment for use underground in caves. Thus, you will have some experience of electronic design, but you are probably not familiar with the adverse conditions presented by caves. It sounds a trivial problem – *caves are wet, so use a waterproof box*. But there is more to it than that. Caves can be a harsh environment.

If you bring your new equipment for testing at a CREG field meeting and the first thing that happens is that a wire falls off; or you install it long-term in BCRA's Cave Science Centre at Poole's Cavern in Derbyshire, and it fills up with water in a month, then you will not be alone. These are common faults that demonstrate why some attention to the basics is advisable.

Because these notes are aimed at electronics *designers*, I will not just limit the discussion to a few basic tips; I will suggest some investigative projects that would make worthwhile dissertations.

In my professional life, I work in the mining industry, where one might also expect equipment to need to be rugged and waterproof. But caves are surprisingly different to mines and are, in some respects, a harsher environment. For one thing, caves can contain large vertical drops, which mining equipment does not survive when accidentally kicked over the edge, as I found out once.

The topics I am going to consider are

- Waterproofing
- Connectors and switches
- Choice of battery

Another aspect I might cover in the future, and which is becoming more important, is how to make sure your networked sensors work properly.

Waterproofing

The salient fact about caves is that they can be very wet. But, of course, not everything has to be watertight. Cameras,

phones, radios... all can work underground without a problem if they are kept dry, and if they are cleaned and dried afterwards. The salient points are how *reliable* is the equipment, and how does it cope with being dropped in a puddle? You cannot work on the assumption that items will not be dropped in water, and that they will not get muddy. You need to design for those conditions. And, of course, if the equipment is going to be installed in a cave (e.g. if it is data logging, or it is a permanent radio station) then it could be dripped on for months, and it must operate in conditions of 100% humidity.

Humidity

Humidity is a particular problem due to the low temperature. In conditions close to 100% relative humidity, it only takes a small drop in temperature for moisture to condense out of the atmosphere, potentially causing your equipment to fail. (See *Box: Humidity*). I'll say some more on this after discussing waterproof enclosures.

Enclosures

If you know a little bit about waterproof housings for electronic components, you will know about the IP (or *ingress protection*) code used to rate the degree of protection provided by enclosures to dust and water [2]. A box that is "pretty much" waterproof will have a rating of IP65, which translates as ...

- Dust-tight
- Water jets (of a certain specification) shall have no harmful effects

The important point is the phrase 'no harmful effects' which, if you think about it, is a strange way to specify an *enclosure* because the potential harm surely depends on what is inside? Nevertheless, enclosures are rated this way.

If you intend to use an IP65 box from an electronic component supplier, and your equipment is likely to get thoroughly

wet, such that the protection is breached, then a simple short-term solution is to build your equipment as a box within a box, perhaps putting the sensitive electronic components within an inner housing. However, this just staves off maintenance work because, at some point, after each use, you are going to have to open up both boxes to dry them out.

HUMIDITY

From *steam tables* (or thermodynamic tables*, to give them their proper name) we can see that the saturated vapour pressure of water at (say) 7.0°C is 1.00kPa. If the relative humidity (RH) is (say) 95%, that corresponds to a vapour pressure of 0.95kPa. The question is what reduction in temperature will cause this moisture to condense. In other words, at what temperature is 0.95kPa the saturated vapour pressure (s.v.p.) of water. Interpolating from the tables, the answer is 6.3°C.

In other words, if you let air at 7°C and 95% RH into your equipment, and the equipment cools by just 0.7°C, water will condense inside the equipment.

Although the relationship is non-linear, it is reasonably linear for small changes, so we can say that, at 7°C the dew point depression is around 0.15°C per 1% RH. In other words, if the cave air is 99% RH – which it could be – then we only need a tiny 0.15°C drop in temperature for moisture to condense.

* I use the book I was issued with as a student 40 years ago [1], but there is bound to be something online now.

Commercially available enclosures to a higher rating – e.g. IP67 (meaning watertight to 1m depth) – are not so widely available. And, again, the key phrase is "Ingress of water in harmful quantity shall not be possible", which does not really help you in the long run.

It is interesting to note why it is that watertight boxes are apparently so diffi-

cult to make. The main problem is the distortion of the seal as the box lid is closed or, significantly, as it is lowered underwater. I wrote in the CREG journal recently [3] on a possible method of construction for pressure-proof housings.

Ingress of Moisture

If you are designing equipment for long-term use in caves, moisture protection is a significant problem, and one which is not solved by using an IP67 housing. That is, you will return to your equipment after several months and likely find that it is full of water – how did the water get in there?

Firstly, note that 1m of water depth is only a tenth of an atmosphere of pressure, i.e. 100 millibar. If an IP67 case is not guaranteed to withstand more than 1m of water pressure, then it will not withstand a change of more than 100mbar of atmospheric pressure. In other words – it will “breathe”. Some people will tell you that the difference in air pressure “sucks in” moisture, but this a dangerous choice of phrase. Dalton’s Law of partial pressures tells us that gases act independently, so it is not possible for movement of one gas to “suck in” another. However, that assumes that the process is a diffusion. If the seal actually distorts as the case breathes, opening up a microscopic channel, then it is conceivable that water vapour could be “sucked in”. Then, as mentioned earlier, it only takes a small drop in temperature for it to condense. I think this must be what is happening, but this is still a puzzling problem and a thorough investigation would make an interesting project.

If the problem is one of “breathing” then a simple way to solve it would be to equalise the pressure inside and out by drilling a hole in the case. This is not such a daft idea, provided that the hole is blocked by a membrane that excludes liquid water. Such components exist and are called *pressure compensation glands*. The UK component distributor Farnell sells a part manufactured by Bopla[4], as shown in the photo below.

Unfortunately, though, it is not possible to exclude water vapour like this – only liquid water. The reason is that a water molecule in its gaseous state is roughly the same size as a molecule of oxygen or nitrogen and could not (easily or cheaply) be excluded by a physical membrane. Liquid water, on the other hand, exists in droplets that are far larger than a single molecule. Thus, a pressure compensation gland prevents the problem of the gross movement of liquid water, and

it protects against the ‘breathing’ of a case seal, but it does not prevent the *diffusion* of water vapour in the long term. However, the diffusion of water vapour through such a small hole would be slow, and possibly so slow that a reasonable supply of silica gel would be able to absorb it. You can see that there is plenty of scope here for experimentation in a student project.



A pressure compensation gland

This features a semi-permeable membrane that excludes liquid water whilst allowing an enclosure to ‘breathe’. The thread is M12.

Another method of preventing ingress of moisture is to equalise the pressure using a diver’s demand valve and a cylinder of air. This method is commonly used by scuba divers to pressurise equipment housings. This would be overkill for many projects that were smaller than a large cabinet full of equipment, but a possible variation on this would make an interesting project.

A mechanical demand valve is a precision piece of equipment, but an electronic replacement might be feasible, using a pressure sensor, a solenoid valve, and a CO₂ vial from a soda siphon. Some mechanical design would probably be necessary as well. Soda siphon vials reportedly contain about 8g of CO₂, expanding to 4 litres when released*.

Another way of maintaining a slight positive pressure would be to heat the inside of the housing. It only needs to be heated to slightly above the ambient temperature of the cave. But even if you insulate the box well, this will take too much power for the scheme to work with long-term battery-operated equipment. (See box: *Thermal Conductivity*).

However, the best way to implement this might be to start with a completely dry box and to use a heater with a humidity sensor in a control loop rather than a temperature sensor. This would make a another interesting and useful student project.

Finally, there is ‘potting’ and the use of inert oil, but I do not want to cover those here, as these are drastic measures, and not really suited to equipment under development.

* CO₂ has a molecular weight of 44, so 8g is about 0.2 mol. 1 mole of a gas occupies ~24 litres at RTP, so 0.2 mol is about 4 litres.

Connectors and Switches

No matter how waterproof you make your enclosure, it will be compromised by the presence of what are called *penetrators* – switches, connectors and the like.

THERMAL CONDUCTIVITY

Suppose you build your equipment into a cubical box with a side of 100mm and wrap it in 15mm of expanded polystyrene insulation. How much power do you need to dissipate inside the box for it to maintain a positive temperature gradient with respect to the outside?

Broadly speaking, heat travels through the polystyrene box as if it were a slab with an area of $A = 6 \times 10^4 \text{ mm}^2$ and a depth of $d = 15 \text{ mm}$.

Suppose the polystyrene has a thermal conductivity of $k \approx 40 \text{ mW/m}\cdot\text{K}$. The power P required to maintain a temperature gradient ΔT is $P/\Delta T = k A/d$ so, in this example, $P/\Delta T = 160 \text{ mW/K}$. If the temperature gradient needs to be only 0.1K, we need a power of 16mW.

A rechargeable AA cell is roughly 2.3Ah at 1.2V, which is 2.7Wh so, at 16mW, the cell would last about 7 days when used for heating in this way. A 100Ω resistor across a 1.2V supply would dissipate just about the required power.

The obvious solution is not to have any penetrators at all, but this is tricky if you need to connect an external sensor.

The next best thing is to use properly-rated switches and connectors. The IP67 rating of a switch is less likely to be compromised than the IP67 rating of a housing, because there is less chance of seal distortion. And, in fact, looking through the catalogues, you will see that IP67 switches are quite common.

However, switches and connectors suffer from problems other than waterproofing, and which can cause cave equipment to fail depressingly often. It is not uncommon for someone to bring an item of equipment into a cave and the first thing that happens is that a wire falls off, or a switch is damaged. You can find plenty of references, on the Internet, to the story related by Buzz Aldrin, the Apollo 11 lunar module pilot, who wrote

“I noticed that the ascent engine arming breaker push/pull switch was broken. Apparently, during movement wearing our large space suit backpacks, either Neil or I bumped into this panel and broke off that particular switch.”

Fortunately, they were able to stick a biro in the hole and waggle it to get the ascent engine to fire.

Make sure your switches cannot be similarly broken by a sharp knock or by dropping the box – because the box *will* be dropped ... and dropped down the largest pitch in the cave.

Make sure you apply strain relief to all wires. For example, if you are soldering wires to a microphone socket, make sure that there is an attachment point for the cable, either a gland that can be screwed tight, or a cable tie placed around the connector post. I make a point of cable-tying all wires to an anchor point on a PCB if they are soldered in position.

A further and unexpected problem with switches and connectors is mud and silt. Cave silt can be an extremely fine powder when dry – like talcum powder. When wet, it can create a thick glutinous paste that dries to a very hard consistency – and it gets *everywhere*. If you are using a camera and you do not wear clean gloves, it is possible to damage the screw thread on a lens by working silt into it.

Switches are vulnerable because of their moving parts. A conventional toggle switch is probably not a good idea to use anyway but, if it is contaminated with even a thin film of mud, it can become unreliable. Traditional switches can be made water and mud-proof by the addition of a sealing boot. (*See photo below*).



Switch seals

Left: waterproof boot for a toggle switch.
Right: shaft seal for a rotary switch.

If you *need* to use a mechanical switch, it might be better to use a rotary switch, which is less likely to fail in the presence of dried mud. Waterproof shaft seals are available (*see above*) but obviously these do not work with a keyed shaft.

A distinct disadvantage of a rotary switch though, is that it can be damaged beyond repair if you try to twist it too far against its stop. Some PCB-mounted switches have very weak stops. A solution to this problem would be to remove the stop altogether – but how will you be able to sense the switch position in the dark?

Switches Without Panel Holes

Several manufacturers now sell control ICs that work with a set of inductive or capacitive switch elements. The salient point is that the inductive or

capacitive element is mounted on the *outside* of the case, and the sensor on the *inside*, with no through-hole required. A cruder version of this would be a reed switch and a magnet. Inductive or capacitive switches might be very useful when you need a keypad, although now and again there is nothing to beat a good old-fashioned toggle switch.

As a student electronic engineer, you might be interested to investigate other solutions. The metal caps off jam-jars and small glass bottles have a very satisfying tactile click. Perhaps the position of the metal could be detected with a Hall effect sensor inside the enclosure?

Data Transmission Without Wires

A simple way to avoid the need for a data connector to download data from your logger is, of course, to use a wireless signal. If you happen to be using a small controller like a Raspberry Pi, then this is trivial because of the built-in wi-fi and Bluetooth. If you do not have that functionality, there are plenty of alternatives – one simple method is to use a transparent housing and an optical modem, utilising an LED.

Choice of Battery

Since these notes are aimed at student electronic engineers, it is pertinent to consider what type of battery you want to use in your design. I will comment on a number of issues which, in summary, are...

- Design for AA and AAA cells; do not use lead-acid or lithium-ion
- Design for interchangeable primary and secondary cells
- Design the system so that individual cells can never be completely discharged
- Consider “human factor” problems, like: can the cells be accidentally inserted in reverse?

Use AA or AAA Cells Only

For environmental and cost reasons, you will probably wish to use rechargeable cells. But there might be an occasion when spare recharged cells are not available, so you need the equipment to be able to run from a widely-available primary cell as well. If your equipment is installed in a cave in the middle of nowhere, and you have to travel to the local shop to purchase something, that places a limitation on the choice of cell.

What this means is that – in my view – your equipment needs to be designed to run on AA or AAA cells, both primary alkaline cells *and* secondary hybrid nickel metal hydride cells[5]. Hybrid cells are the new low self-discharge type, sometimes

known as ‘accu’ cells; and are sold in the larger supermarkets in the UK, but perhaps not yet in every corner shop.

If you find yourself thinking that you need to use lead-acid or lithium-ion batteries, or some more exotic coin cell or other specialist battery, then you are simply stacking up problems for later on, and I would urge you to reconsider.

Primary AA/AAA cells come in a range of capacities and shelf-lives, including some extremely long-life cells. I was once involved in designing some equipment that needed a standby (zero current) life-time of twenty years, so a lithium primary cell is about the only choice possible for that. For most applications, though, a number of hybrid NiMH AA cells (2.3Ah / 2.7Wh) will do the job.

Primary vs. Secondary Cells

I explained, above, that you need to design for interchangeable primary and secondary cell. Unfortunately, the terminal voltage of NiMH cells is only 1.2V, as opposed to 1.5V for primary alkaline cells. It is imperative that your equipment works with both voltages.

For example, I use a rechargeable cell in my Bluetooth computer mouse but, barely have I inserted a fresh cell than it warns me of a low battery voltage, as the device has not been designed with the above point in mind.

Prevent 100% Discharge

If you want to design your equipment to a really high standard of performance, you must make sure that the cells cannot *individually* run completely flat. This is, of course, a chore if you are using several cells in series, because monitoring the overall voltage might not be enough.

The danger of allowing complete discharge is that cells will not all discharge with the same characteristic, and the weakest cell in the chain will go flat first. Then, if the equipment continues to draw power, the weakest cell will reverse charge, which damages it. There are essentially three approaches to this problem.

- Do not use multiple cells in series
- Monitor the voltage of each cell
- Monitor the voltage of the power rail and make an ‘intelligent’ assessment of the health of the cells

The first option is the most ideal. You can utilise a voltage booster circuit to give you the voltage that you require. This is fine for low-power equipment but obviously more of an issue for a power-hungry device, like a radio transmitter.

Monitoring the voltage of each cell might seem wasteful of components but, provided you do not have too many cells in series, it is possible to monitor only the *overall* voltage and to determine (with a fair degree of certainty) whether you have N cells, all approaching their endpoint voltage of 1.0V or $N-1$ cells that are still fresh (1.2V each) and just one that has died (0V).

For example, if you were using four cells in series, you could assume that 4.0V was a sensible end-point. A little maths demonstrates that, with the above scheme, you cannot have more than six cells in series, because, in that situation you could only just distinguish between a valid end-point of 6.0V and the case where five cells were fresh and one dead.

So here is yet another possible student project: study this assertion on voltage measurement and see if it is workable.

Reverse Fitting of Cells

If you are fumbling in the dark with numb hands, how can you be sure that you have inserted a fresh set of cells the correct way around?

Having your equipment feature a special battery-changing light is one solution (but how will you power it?) Another is for your equipment not to mind if the cells are connected in random orientations. Placing a bridge rectifier around each cell is probably overkill, not to mention being wasteful of power (due to the dissipation in the diodes), but there are more efficient solutions using bootstrapped mosfets. Further possibilities and variations on the above themes may occur to you.

If your system *does* feature current steering circuits, then one spin-off is that the cells do not need to be connected in series. You can achieve a high power by connecting a number of cells in parallel, via current-sharing circuits (i.e. bootstrapped mosfets or, at a pinch, diodes). This neatly solves the associated problem of monitoring the cell voltages and preventing reverse charging.

Further Reading

The CREG Journal has featured many articles on the mechanical aspects of equipment design. Many of these have been in our *Wet and Dry* column, edited in recent years variously by Mike Bedford and Tony Haigh. The best way to search for these is to use the CREG search engine. [6]. Just type "Wet & Dry" into the search box. At the time of writing there are 41 articles in this series – some more useful

than others, no doubt, but all with a range of tips and suggestions.

Student Projects

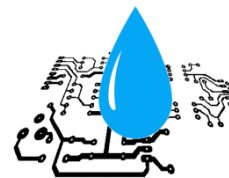
Projects and investigations mentioned in the main text included...

- Why do sealed enclosures, in a cave environment, apparently suffer from ingress of water over a period of many months?
- How fast does water vapour diffuse through a pressure compensation gland? How long can silica gel protect against such diffusion?
- Design a device to protect against moisture ingress, using a CO₂ vial to keep the enclosure under a very small positive pressure
- Can a very low power heater be used with a pressure compensation gland to keep moisture out of an enclosure?
- Design a keypad that can be used with gloved hands, which uses 'snappable' bottle caps as the keyable elements, with the sensors placed on the inside of a sealed case
- Design an optical modem to provide very low power data communication with a sealed (but transparent) enclosure
- Design a circuit to handle, with minimal power loss, the reverse connection of a random number of cells in a battery pack, and to monitor for (or successfully predict) the presence of a dead cell

References

URLs checked on 26-Feb-2020

- [1] Hayward, R.W. (1972), *Thermodynamic Tables in SI (Metric) Units*, Cambridge University Press, 2nd edition, ISBN 0 521 09714 2
- [2] wikipedia.org/wiki/IP_Code
- [3] Gibson, David (2018), *Simple Enclosure is Waterproof to 400 Metres*, CREGJ **104**, pp3–6. Dec. 2018. bcra.org.uk/cregj/?j=104
- [4] uk.farnell.com/bopla/52042000/pressure-comp-element-pk5/dp/4455824
- [5] Gibson, David (2008), *Batteries for the 21st Century*, CREGJ **70**, pp18–19. March 2008. bcra.org.uk/cregj/?j=70
- [6] bcra.org.uk/pub/cregj/search.html



Wet & Dry

Mike Bedford reviews an approach for in-cave computing.

Rugged laptops have been discussed and reviewed in *CREGJ* on several occasions. All are considerably more expensive than ordinary laptops and, unless you pay a huge amount, most could not really be considered cave-proof. This has left users of laptops underground to take risks. The further development of an initiative by Jay Doscher might offer an affordable solution.

Described on his website at back7.co/home/raspberry-pi-recovery-kit, Jay's creation is a rugged and waterproof portable PC based on a Raspberry Pi. It's housed in a Pelicase with the addition of some 3D-printed parts, and includes a touch-sensitive LCD screen and a power source. It also makes USB and GPIO ports available via rugged connectors.



Being concerned about the usability of a touch screen with wet hands or in the presence of dripping water, I took up the issue of cave-proofing with Jay. I was disappointed to discover, though, that while this computer was designed to be waterproof in transit, it was not a design requirement that it would be waterproof in use, as Jay explained. "I don't think my project is a good fit for you in its current form. While my project is designed to sit inside an unmodified Pelican case, once opened, it's quite sensitive to moisture. All of the electronics are essentially in the 'bucket' lower half of the enclosure, so stray water would be pretty bad. You're right to point out that the touch screen would not work well in wet environments either." He did offer some encouragement for those who might be inspired to adopt a similar approach for cave use, though. "I think you could make one that would stay waterproof inside a Pelican case with the lid open", he said.

Web Watch



Peter Ludwig offers a couple of links of interest...

Some possibilities for expedition power, in addition to advances in electric vehicle range: lancaster.ac.uk/news/new-material-could-unlock-potential-for-hydrogen-powered-vehicle-revolution

Penetration 'test' of a lithium battery. Be warned! t.co/naoxtaFE4C

A battery survey: proaudioeng.com/portable-battery-performance/

